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Quality, Reliability, Human and Organization Factors in Design of Marine Structures

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ABSTRACT

Experience has amply demonstrated that Human and Organization Factors (HOF) play important roles in determining the quality and reliability of marine structures such as ships, pipelines, and offshore platforms. This paper addresses HOF in the context of quantitative reliability analyses that are intended to help improve the quality of marine structures. Quality is defined as the combination of acceptable and desirable serviceability, reliability, durability, and compatibility in a marine structure.

A classification of HOF is proposed that addresses individual, organization, equipment / hardware, procedures / software, and environmental considerations. Alternatives for improved management of HOF are addressed including Quality Assurance and Quality Control (QA / QC), and design of error tolerant structures. A generic design process for marine structures is defined. Based on these developments, a generic Quantitative Risk Analysis (QRA) is developed that addresses HOF in addition to the structure system aspects that have been traditionally addressed by QRA. Error promoting characteristics of complex design guidelines and computer software are discussed.

A companion paper illustrates application of these developments to a ship structure problem involving design of the critical details for fatigue (Bea, 1995).

QUALITY

Quality is defined as freedom from unanticipated defects. Quality is fitness for purpose. Quality is meeting the requirements of those that own, operate, design, construct, and regulate marine structures. These requirements include those of *serviceability, safety, compatibility, and durability* (Matousek, 1990) (Figure 1).

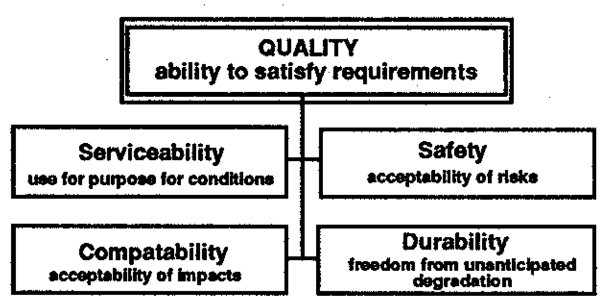

FIGURE 1 - ATTRIBUTES THAT CONSTITUTE QUALITY OF MARINE STRUCTURES

Serviceability is suitability for the proposed purposes, i.e. functionality. Serviceability is intended to guarantee the use of the system for the agreed purpose and under the agreed conditions of use. Safety is the freedom from excessive danger to human life, the environment, and property damage. Safety is the state of being free of undesirable and hazardous situations. The capacity of a structure to withstand its loadings and other hazards is directly related to and most often associated with safety. Compatibility assures that the system does not have unnecessary or excessive negative impacts on the environment and society during its life-cycle. Compatibility also is the ability of the system to meet economic and time requirements. Durability assures that serviceability, safety, and environmental compatibility are maintained during the intended life of the marine system. Durability is freedom from unanticipated maintenance problems and costs.

RELIABILITY

Reliability (Ps) is closely related to quality. Reliability is defined as the probability that a given level of quality will be achieved during the design, construction, and operating life-cycle phases of a marine structure. Reliability is the likelihood that the system will perform in an acceptable manner. Acceptable performance means that the system has desirable serviceability, safety, compatibility, and durability. The compliment of reliability is the likelihood or probability of unacceptable performance; the probability of "failure" (Pf).

Likelihoods of not realizing a desirable level of quality arise because of a wide variety of uncertainties. During the design phase there is a likelihood of not realizing the intended quality due to causes such as an analytical flaw embedded in a finite element program or an error made in interpreting a design loading formulation. During the construction phase, unrealized quality might be developed by the use of the wrong materials or use of inappropriate alignment and welding procedures. During the operating phase, unrealized quality might be developed by accidental loading from collisions or dropped objects or neglect of planned maintenance of coatings and cathodic protection.

Reliability can be expressed analytically as

$$Ps = [1-Pf] = P[D \leq C] = 1 - Pf \qquad (1)$$

where D is the demand placed on the marine structure system and C is the ability or capacity of the system to meet or satisfy the demand. P [x] is read as the probability that the event [x] takes place. Demands and capacities are quantified in terms meaningful to define serviceability (e.g. days available for service), safety (e.g. margin between load resistance and loading), durability (e.g. expected life of structure), and compatibility (e.g. expected initial and future costs).

Generally, structural reliability has been defined as the likelihood that the marine structure's capacity is exceeded by the dead, live, and environmental loading. This definition has been criticized because of its limited scope. Conventional structural reliability analysis fails to address the other key issues associated with the quality of the marine structures. The conventional definition frequently fails to address the other key hazards to the quality of the structure that develop during the life-cycle of the structure (design, construction, operation).

Unreliability is due fundamentally to three types of uncertainties (Bea, 1990). The first is inherent or natural randomness (aleatory). The second is associated with analytical or professional uncertainties (epistemic). The third is associated with errors made by individuals and groups of individuals or organizations (human errors) (Bea, Moore, 1991, 1992).

While conventional structural reliability assessments have explicitly addressed the first two types of uncertainty, in general they have not addressed the third category of uncertainty. At best, the third category of uncertainty has been included implicitly. It has been incorporated in the background of data and information that is used to describe the uncertainties and variabilities. This paper develops a reliability based formulation which explicitly addresses the attributes of quality, the life-cycle phases (design, construction, operation) and Human and Organization Factors (HOF).

HOF CLASSIFICATION

Human and organization interrelationships with systems, procedures, and environments (internal, external) can be organized as shown in Figure 2. There are error producing potentials within each of the primary sectors including the human operators (designers, constructors, operators), the organizations that influence these operators, the systems themselves (hardware), the documentation that embody the manuals of use or practice for the systems (software), and finally the external and internal environments. In addition to the error producing potentials within each of these sectors, there are error producing potentials at the interfaces of the sectors.

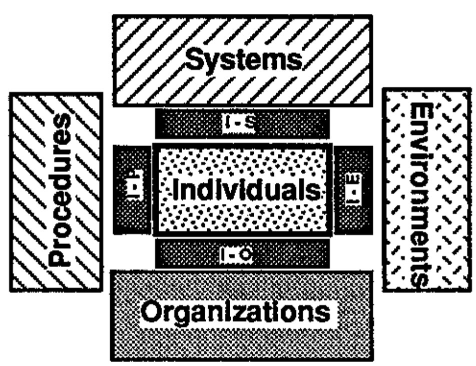

FIGURE 2 - COMPONENTS AND INTERFACES THAT CAN LEAD TO HUMAN ERRORS

Human Errors

There are many different ways to classify and describe human errors. The classification system developed herein is intended for use with reliability based qualitative and quantitative methods that are intended to help improve the quality of marine structures.

Human errors can be defined as actions taken by individuals that can lead an activity (design, construction, operation) to realize a lower quality than intended. These are errors of commission. *Human errors also include actions not taken that can lead an activity to realize a lower quality than intended.* These are errors of omission. Human errors might best be described as "action and inaction that result in lower than acceptable quality" to avoid implications of blame or shame. Human errors also have been described as "mis-administrations." and "unsafe actions."

Human errors can be described by types of error mechanisms (Reason, 1990). These include slips or lapses, mistakes, and circumventions. Slips and lapses lead to low quality actions where the outcome of the action was not what was intended. Frequently, the significance of this type of error is small because that these actions not being as intended are easily recognized by the person involved and in most cases easily corrected.

Mistakes can be developed while the action was as intended, but the intention was wrong. Circumventiens (or violations) are developed where a person decides to break some rule for what seems to be a good (or benign) reason to simplify or avoid the task.

Mistakes are perhaps the most significant because they are followed purposefully by the user who has limited clues that there is a problem. Often, it takes an outsider to the situation to identify mistakes.

Based on a study of available accident databases on marine systems and study of case histories in which the acceptable quality of marine systems has been compromised (Moore, Bea, 1993a), the primary factors which can result in human errors are identified in Figure 3 (Bea, Moore, 1994). The sources of mistakes or cognitive errors are further detailed in Figure 4.

This human error classification (taxonomy) is intended to allow the exclusive and exhaustive identification of how individuals can make errors in the design, construction, and operation of marine structures.

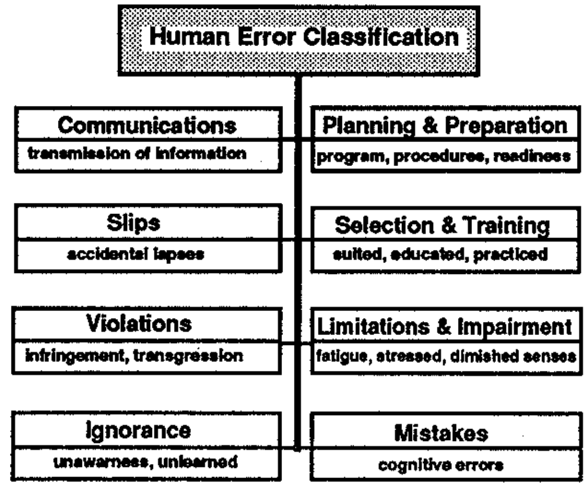

FIGURE 3 - CLASSIFICATION OF HUMAN ERRORS

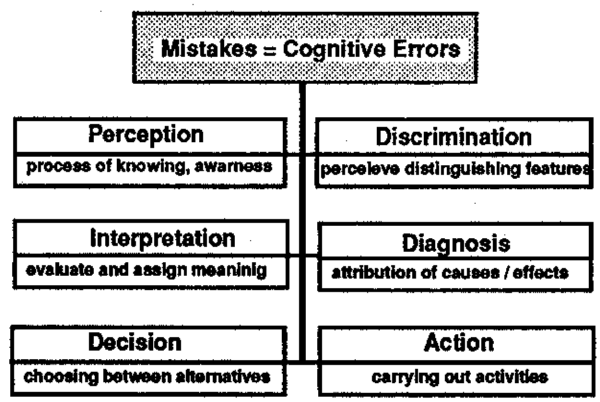

FIGURE 4 - CLASSIFICATION OF COGNITIVE ERRORS

Organization Errors

Analysis of past decisions regarding the design, construction, and operation of marine structures provides numerous examples of instances in which organizational failures have resulted in failures of marine systems (Wenk, 1986; Paté-Cornell, Bea, 1989; 1992; Petroski, 1985; Perrow, 1984; Moore, Bea, 1993b; Moore, 1994). Either collections of individuals (organizations, teams) or individuals (unilateral actions) contribute to accident situations. Failures can occur as a result of an organization's or an individual's willingness to take a calculated risk. Failures can result from different types of inevitable errors that can be corrected in time, provided they are detected, recognized as errors, and corrective action is promptly taken (Roberts, 1989, 1990, 1993). Failures can also occur as the result of errors or bad decisions, most of which can be traced back to organizational malfunctions.

The goals set by the organization may lead rational individuals to conduct operations on a marine structure in a manner that corporate management would not approve if they were aware of their reliability implications. Similarly, corporate management, under pressures to reduce costs and maintain schedules, may not provide the necessary resources required to achieve desirable levels of quality.

Generally, two classes of problems face an organization in making collective decisions that result from sequences of individual decisions: information (who knows what and when?), and incentive (how are individuals rewarded, what decision criteria do they use, how do these criteria fit the overall objectives of the organization?). In development of programs to improve management of HOF, careful consideration should be given to information (collection, communications, and learning) and incentives, particularly as they affect the balancing of several objectives such as costs and safety under uncertainty in operations of offshore platforms.

The structure, the procedures, and the culture of an organization contribute to the safety of its product and to the economic efficiency of its quality management practices (Roberts, Bea, 1995). The organization's structure can be unnecessarily complex and demand flawless performance (Koch, 1993). This can result in little or no credible feedback to the upper levels of management. The resulting safety problem is that there may be inconsistencies in the decision criteria (e.g. safety standards) used by the different groups for various activities. This can result in large uncertainties about the overall system safety, about the reliability of the interfaces, and about the relative contribution of the different subsystems to the overall failure probability.

Organization and management procedures that affect system reliability include, for example, to save time, parallel processing such as developing design criteria at the same time as the structure is being designed, a procedure that may or may not be appropriate in economic terms according to the costs and the uncertainties (Paté-Cornell, Bea, 1992). Other examples can be cited as a result of present corporate efforts to "down-size" and "out-source." Loss of corporate memories (leading to repetition of errors), creation of more difficult and intricate communication interfaces, unwarranted reliance on the expertise of "outside contractors" and inexperienced personnel, cut-backs in quality assurance and control, and provision of conflicting incentives (e.g. cut costs, maintain quality) are examples of activities that can lead to substantial compromises in the intended quality of marine structures.

Experience indicates that one of the major factors in organizational error is the "culture" of the organization (Roberts, 1989; 1993; Koch, 1993; Roberts, Bea, 1995). For example, the dominant culture may reward risk seeking (flirting with disaster) or superhuman endurance (leading to excessive fatigue), an attitude that in the long run may prove incompatible with the objectives of the organization. Another feature may be the lack of recognition of uncertainties leading to systematic biases towards optimism and wishful thinking.

Organization error is defined as a departure from acceptable or desirable practice on the part of a group of individuals that results in unacceptable or undesirable results. A classification of organization errors is given in Figure 5.

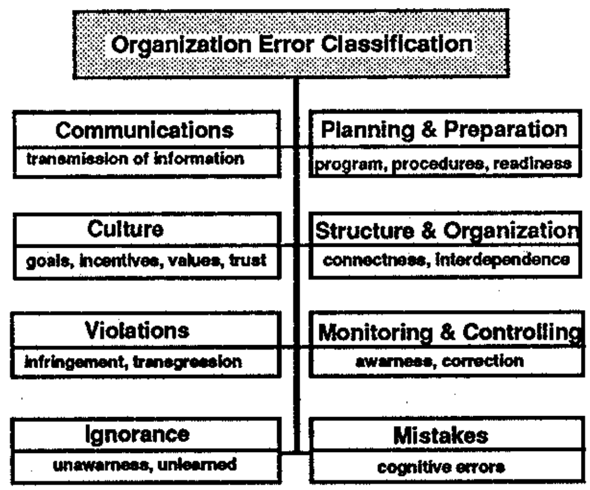

FIGURE 5 - CLASSIFICATION OF ORGANIZATION ERRORS

System & Procedure Errors

Errors can be initiated by or exacerbated by poorly engineered systems and procedures that invite errors (Miller, 1990; ASTM, 1993). Such systems are difficult to construct, operate, and maintain.

New technologies compounds the problems of latent system flaws (Wenk, 1986). Complex design, close coupling (failure of one component leads to failure of other components) and severe performance demands on systems increase the difficulty in controlling the impact of human errors even in well operated systems (Perrow, 1984; Petroski, 1985; Reason, 1991).

Emergency displays have been found to give improper signals of the state of the systems. Land based industries can spatially isolate independent subsystems whose joint failure modes would constitute a total system failure.

System errors resulting from complex designs and close coupling are more apparent due to spatial constraints aboard ships and platforms. The field of "ergonomics" has largely developed to address the human - machine or system interfaces. Specific guidelines have been developed to facilitate the development of "people friendly" systems (ASTM, 1993).

Figure 6 summarizes a classification system for system or hardware related errors. These errors range from insufficient capacity and durability to unacceptable serviceability and compatibility.

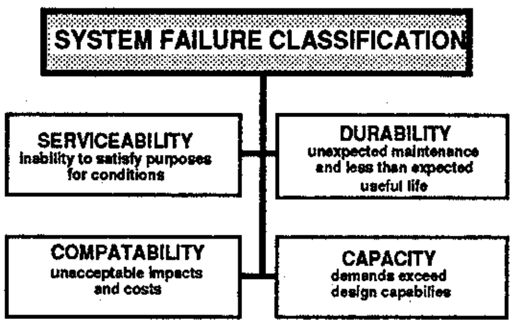

FIGURE 6 - CLASSIFICATION OF SYSTEM ERRORS

The issues of system robustness (defect or damage tolerance), design for constructablity, and design for IMR (Inspection, Maintenance, Repair) are critical aspects of engineering marine structures that will be able to deliver acceptable quality (Bea, 1992; 1993, 1994a). Design of the structure system to assure robustness is intended to combine the beneficial aspects of redundancy, ductility, and excess capacity (it takes all three). The result is a defect and damage tolerant system that is able to maintain its serviceability characteristics in the face of HOF. This has important ramifications with regard to structural design criteria and guidelines (Bea, 1991). Design for constructability and IMR have similar objectives.

Figure 7 summarizes a classification system for procedure or software errors. These errors can be embedded in engineering design guidelines and computer programs, construction specifications, and operations manuals. With the advent of computers and their integration into many aspects of the design, construction, and operation of marine structures, software errors are of particular concern because "the computer is the ultimate fool." Software errors in which incorrect and inaccurate algorithms were coded into computer programs have been at the root cause of several major failures of marine structures (Bea, Moore, 1994). Guidelines have been developed to address the quality of computer software for the performance of finite element analyses. Extensive software testing is required to assure that the software performs as it should and that the documentation is sufficient. Of particular importance is the provision of independent checking procedures that can be used to validate the results from analyses. High quality procedures need to be verifiable based on first principles, results from testing, and field experience.

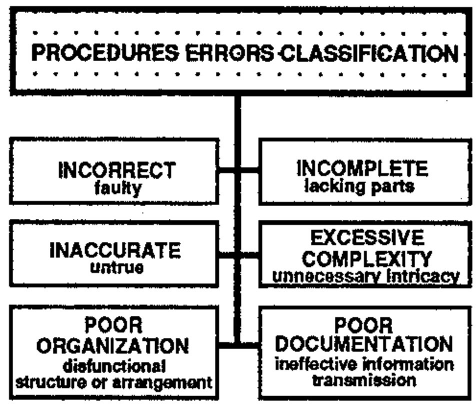

FIGURE 7 - CLASSIFICATION OF ERRORS IN PROCEDURES

Given the rapid pace at which significant industrial and technical developments have been taking place, there has been a tendency to make design guidelines, construction specifications, and operating manuals more and more complex. In many cases, poor organization and documentation of software and procedures has exacerbated the tendencies for humans to make errors. Simplicity, clarity, completeness, accuracy, and good organization are desirable attributes in procedures developed for the design, construction, and operation of marine structures.

The next section of this paper will apply the classification systems for individual, organization, hardware, and software errors to development of a reliability formulation that addresses structure design, construction, and operation. In this development, the human error classifications (individuals, organization, hardware, procedures, systems) that were developed in the previous section are assumed to identify sets of mutually exclusive and exhaustive HOF causes.

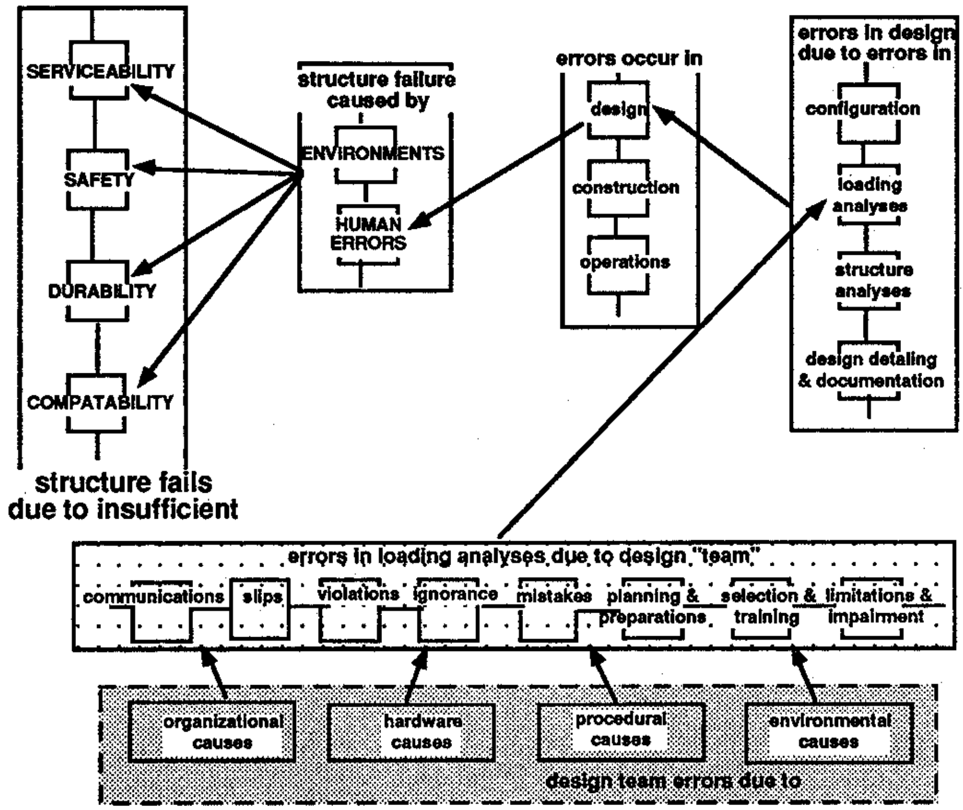

FIGURE 8 - SYSTEM RELIABILITY ANALYSIS INCLUDING HOF

RELIABILITY FORMULATION

A system diagram expression of HOF influences on the quality of a marine structure is illustrated in Figure 8. A quantitative probabilistic reliability formulation will be developed based on the approach embodied in Figure 8.

Starting at the left of Figure 8 and proceeding to the right (following the arrows backwards), the four attributes of structure quality are identified. These attributes can be compromised by environmental hazards and / or human errors. Human errors can occur in design, construction, and / or operations.

This system diagram focuses on the structure design. This activity is divided into four generic parts: configuration, loading analyses, structure analyses, and design detailing and documentation (Bea, 1994; Bea, et al., 1994). Human errors could occur in one or all of these parts. The diagram indicates the evaluation of a human error that occurs in the design loading analyses.

The error in the loading analyses could be due to "design team" errors that are due to communications, etc. (Figure 3). These errors could be attributed to organization, hardware, and / or software errors (Figures 5 through 7). In the more general case, environmental conditions could also cause errors (Figure 2).

First Level - Failure to Achieve the Desired Quality

The *System* in Figure 8 refers to the marine structure system. The quality of the structure system can be directly influenced by two primary categories of factors: 1)*Environments* (E), and 2) *Human & Organization Factors* (O).

The category Environments represented by E are hazards that can result in compromises in the quality of the structure that are "natural" or due to inherent randomness. The category of HOF represented by O represent hazards that can result in compromises in the quality of the structure that are "unnatural" or due to HOF.

The structure quality attributes are defined as serviceability, safety, durability, and compatibility. An insufficient quality attribute ($i = 1$ = serviceability, $i = 2$ = safety, $i = 3$ = durability, $i = 4$ = compatibility) can be caused by *natural causes / inherent randomness (E)* and / or *HOF (O)*.

The likelihood of insufficient quality in the structure is indicated as the probability of failure (Pf_Q). The likelihood of insufficient quality (failure) is the union ($\cup$) of the likelihoods of insufficient serviceability, Pf_1, safety, Pf_2, durability Pf_3, and compatibility Pf_4

$$Pf_Q = \cup Pfi \quad (i = 1 \text{ to } 4) \tag{2}$$

Insufficient Quality - With and Without HOF

The probability of failure of any one of the quality attributes due to inherent randomness will be identified as Pfi_E. The probability of failure of any one of the quality attributes due to the occurrence of human error will be identified as Pfi_O. Then

$$Pfi = \{Pfi_E \mid O\} P[O] + \{Pfi_E \mid \emptyset\} P[\emptyset] + Pfi_O P[O] \tag{3}$$

where

$$P[\emptyset] = 1 - P[O] = \text{probability of no human error} \tag{4}$$

and A I B indicates the occurrence of A conditional on the occurrence of B.

Life-Cycle Phases of Quality

The likelihood of insufficient quality in the structure due to HOF could be evaluated in the design (Y_1), construction (Y_2), and operations (Y_3) phases as follows

$$Pfi_O = \cup Pf [Yi \mid O_{Yi}] P [O_{yi}] \quad (i = 1 \text{ to } 3) \tag{5}$$

where Oyi indicates a human error that occurs in one of the three life-cycle phases of the structure.

Quality In One Phase of the Life Cycle (Design)

The likelihood of insufficient quality in the structure due to the influences of individuals during the design phase (1.0) could be evaluated as follows

$$Pfi[Y_1 \mid O_{Y1}] = Pfi[Y_{1.1} \mid O_{Y1.1}] P [O_{Y1.1}] \cup Pfi[Y_{1.2} \mid O_{Y1.2}] P [O_{Y1.2}] \cup Pfi[Y_{1.3} \mid O_{Y1.3}] P [O_{Y1.3}] \cup Pfi[Y_{1.4} \mid O_{Y1.4}] P [O_{Y1.4}] \tag{6}$$

where the subscripts 1.1, 1.2, 1.3, and 1.4 refer to the configuration of the structure, the loading analyses, the structure analyses, and the design documentation, respectively. These are the four major components that have been identified to form the design activities (Figure 8).

Quality In One Part of One Phase of the Life Cycle (Loading Analyses)

The likelihood of insufficient quality in the structure due to human error during the loading analyses could be evaluated as follows

$$Pfi[Y_{1.2}] = \cup (Pfi \mid Oj) P[Oj \mid Y_{1.2}] \quad (j = 1 \text{ to } 8) \tag{7}$$

where (Pfi I Oj) refers to the probability of insufficient quality of Type i (serviceability, safety, durability, compatibility) of the structure due to (conditional upon) a human error of Type j. P[Oj] refers to the probability of the human error of Type j. The human error Type j subscripts 1 through 8 refer to the individual human error classification system summarized in Figure 3.

(Pfi I Oj) is the "fragility" curve for the structure (Figure 9). This fragility curve characterizes the probability of failure of the structure conditional on the occurrence of a type and intensity of human error. Such a fragility curve could be developed analytically by determining how the particular quality characteristic of the structure (e.g. its capacity or durability) is influenced by different types and "intensities" of errors. Several examples of structure design fragility curves have been developed by Bea (1994).

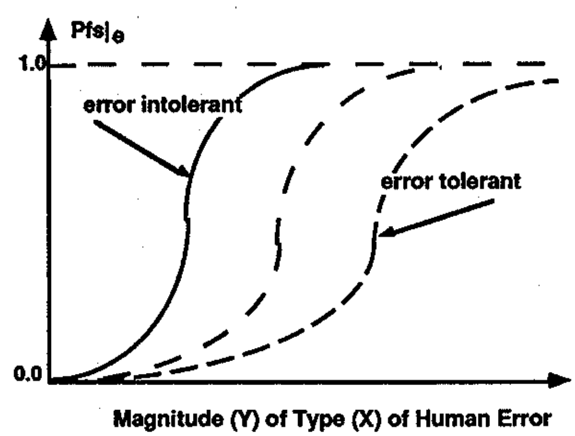

FIGURE 9 - LIKELIHOOD OF UNSATISFACTORY QUALITY FOR ERROR TOLERANT AND INTOLERANT STRUCTURE ELEMENTS

Explicit evaluation of variable error intensities or magnitudes could be avoided if it were assumed that the errors addressed were those that resulted in very significant or major degradation in quality. This would be equivalent to defining only two categories of errors: major and minor. It then would be necessary to determine the probability of failure associated with the defined major category of error. Such a definition is consistent with the meager quantitative data that is available on human errors (Bea, 1994).

It is important to note that the shape of the fragility curve can be controlled by engineering. *This is explicit design for "robustness" or defect (error) tolerance* (Bea, 1991). For the intensities (magnitude) and types of errors that normally can be expected, the structure should be configured and designed so that it does not "fail" (or have unacceptable quality) when these types and magnitude of errors occur (Bea, 1992; Das, Garside, 1991).

The likelihood of insufficient quality developing in the other three parts of the design process (configuration, structure analyses, and design documentation) would be developed in a manner similar to the foregoing.

Contributing Influences to Human Errors

The categories of human errors are influenced by four types of contributing influences (error inducing or causing factors): *organizations (Oe), hardware (He), procedures (Pe), and environment (Ee).*

The probability of a given type (e.g. communications) and magnitude (e.g. major) of a human error (Oj) made by the individual or individuals comprising a given part of the design "team" in the loading analysis during the design phase ($Y_{1.2}$) could be evaluated as follows (Figure 8)

$$P[Oj \mid Y_{1.2}] = P[Oj \mid Oej]\, P[Oej] \cup P[Oj \mid Hej]\, P[Hej] \cup P[Oj \mid Pej]\, P[Pej] \cup P[Oj \mid Eej]\, P[Eej] \quad (8)$$

where P[Oej], P[Hej], P[Pej], and P[Eej], refer to a human error of type j caused by organization factors, hardware factors, procedure factors, and environment (internal) factors, respectively.

Causes of Contributing Influences

The probability of the organization influence on the human error of a given type (Oj) occurring during the design phase in the loading analysis ($Y_{1.2}$) could be expressed as follows

$$P[Oej \mid Y_{1.2}] = \cup\, P(Oejn) \quad (n = 1, ..., 8) \quad (9)$$

The subscripts n = 1 through n = 8 refer to the organization error classification system summarized in Figure 5.

The other terms (P[He], P[Pe], and P[Ee] would be developed in the same manner as P[Oe].

System Diagram - Rare Event Approximation

The system diagram shown in Figure 8 has been based on the rare event approximation of the foregoing analytical expressions. Consistent with these developments, all of the direct and contributing factors have been shown as elements in series. In this case, the following expressions can be developed.

The likelihood of insufficient quality is

$$Pf_Q \approx \Sigma\, Pfi \quad (i = 1 \text{ to } 4, \text{ four attributes of quality}) \quad (10)$$

The likelihood of insufficient quality in a given attribute due to "natural causes" (E) and due to "human errors" (O) is

$$Pfi = \{Pfi_E \mid O\}\, P[O] + \{Pfi_E \mid \emptyset\}\, P[\emptyset] + Pfi_O\, P[O] \quad (11)$$

The likelihood of human error causing insufficient quality in a phase of the life-cycle is

$$Pfi_O \approx \Sigma\, Pf\, [Yi \mid O_{Yi}]\, P\, [O_{Yi}] \quad (i = 1 \text{ to } 3, \text{ three life-cycle phases}) \quad (12)$$

The likelihood of human error causing insufficient quality in one of four parts of the design phase (1.1 = configuration, 1.2 = loading analyses, 1.3 = structure analyses, and 1.4 = design documentation is

$$Pfi[Y_1 \mid O_{Y1}] = Pfi[Y_{1.1} \mid O_{Y1.1}]\, P\, [O_{Y1.1}] + Pfi[Y_{1.2} \mid O_{Y1.2}]\, P\, [O_{Y1.2}] + Pfi[Y_{1.3} \mid O_{Y1.3}]\, P\, [O_{Y1.3}] + Pfi[Y_{1.4} \mid O_{Y1.4}]\, P\, [O_{Y1.4}] \quad (13)$$

The likelihood of human error causing insufficient quality in the loading analyses part of the design phase caused by the eight types of human errors is

$$Pfi[Y_{1.2}] \approx \Sigma\, (Pfi \mid Oj)\, P[Oj \mid Y_{1.2}] \quad (j = 1 \text{ to } 8, \text{ types of human errors}) \quad (14)$$

The likelihood of one of the eight types of human errors (Oj) caused by one of the four principal causes or influences acting during the design loading analyses is

$$P[Oj \mid Y_{1,2}] = P[Oj \mid Oej]\, P\, [Oej] +$$

$$P[Oj \mid Hej]\, P\, [Hej] + P[Oj \mid Pej]\, P\, [Pej] +$$

$$P[Oj \mid Eej]\, P\, [Eej] \qquad (15)$$

The likelihood of a human error due to eight organizational influences occurring during the design phase is

$$P[Oej \mid Y_{1,2}] \approx \Sigma\ P(Oejn)$$
$$(n = 1, ...,8) \qquad (16)$$

Observations

These approximate analytical expressions equate to a series system that determines the quality of a structure. This is an interesting observation of the *quality system*. As additional elements are added to a series system comprised of *independent* elements, its probability of failure increases. This indicates that the number of primary activities in all parts of the structure design process should be decreased to the minimum possible to decrease the likelihood of the system not developing the desirable level of quality. This emphasizes the importance of "team work" and integration of activities throughout the design phase in which members of the design team are trained and experienced in performing all of the design activities. This turns the chain link system into a redundant parallel element system.

The other interesting observation regards the effects of correlation between the series elements. If all of the series elements are highly positively correlated, then the probability of failure of the system is equal to the greatest probability of failure in the system series *chain*. The reliability of a multi-element series system can be improved by high positive correlation. High positive correlation in the system elements could be developed by human factors such as a consistent set of high quality individual (human), organization, hardware, and procedures factors that are allowed to permeate the entire design process. Organization culture is likely the most important of the correlating processes [Roberts, Bea, 1995].

QUALITY ASSURANCE & CONTROL

Quality Assurance (QA) are those practices and procedures that are designed to help assure that an acceptable degree of quality is obtained. Quality assurance is focused on prevention of errors. Quality Control (QC) is associated with the implementation and verification of the QA practices and procedures. Quality control is intended to assure that the desired level of quality is actually achieved. Quality control is focused on reaction, identification of errors, rectification, and correction.

QA / QC measures are intended to assure that a desirable and acceptable reliability of the marine structure is achieved throughout its life (Bea, et al., 1994). Achieving quality goals is primarily dependent on people. QA / QC efforts are directed fundamentally at assuring that human and system performance is developed and maintained at acceptable levels.

Figure 10 outlines the strategies that can be employed in defining QA / QC measures. These strategies include those put in place before the activity (prevention), during the activity (checking), after the activity (inspection), after the manufacture or construction (testing), and after the structure has been put in service (detection). The earlier QA / QC measures are able to detect the lack of acceptable quality, then the more effective can be the remediation.

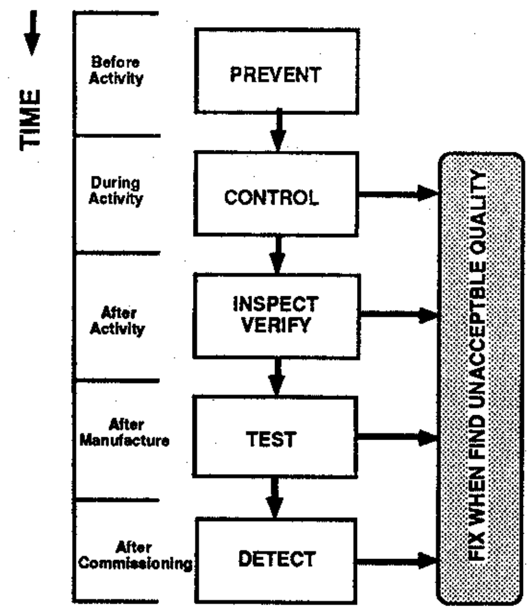

FIGURE 10 - QUALITY ASSURANCE AND CONTROL STRATEGIES

Of all of the QA / QC measures, the most effective are those associated with prevention. As factors leading to lack of desirable quality are allowed to become more and more embedded in first the design, then the construction, and then the operation of a marine structure, then the more difficult they are to detect and correct. Personnel selection, training, and verification; the formation of cohesive teams and encouragement of teamwork, and the elimination of unnecessary complexity in procedures and structure - equipment systems are examples of effective QA / QC measures.

Control QA / QC measures consist of procedures and activities that are implemented during design and construction activities to assure that desirable quality is achieved. Self-checking, checking by other team members, and verification by activity supervisors are examples of such activities.

Inspection and verification QA / QC measures consist of procedures and activities that are implemented after the design and construction activity or segment of that activity has been completed. Design documentation and construction production products are inspected to assure compliance with the applicable procedures and specifications. Verification of design assumptions and analyses and destructive and non-destructive testing of constructed elements are examples of such activities.

Detection QA / QC measures consist of procedures and activities that are implemented after the marine structure has been put in service to assure that desirable and acceptable quality are maintained. The use of instrumentation and monitoring systems and in-service inspections to assure that significant unanticipated damage is not developing in the structure due to cracking and corrosion are examples of such activities.

QA / QC In Reliability Formulation

In the earlier reliability based formulation, it was assumed that there has been no explicit QA / QC in the system. Stated in another way, the human error rates that would be used in such an analysis would presume that there was no unusual *defense in depth* provided to detect and correct errors. In one way, this is not unreasonable. Most minor errors are caught by the individual or individuals involved in a particular process and corrected. In this development, we are concerned with the *major embedded errors* that can lead to significant degradation in quality that are not caught at the local level.

Consequently, the next step in this development addresses human error detection (D) and correction (repair, C). This is an attempt to place parallel elements in the quality system (Figure 8) so that *failure* of a component (assembly of elements) requires the failure of more than one *weak link*. Given the high positive correlation that could be expected in such a system, this would indicate that QA / QC efforts should be placed in those parts of the system that are most prone to error or likely to compromise the intended quality of the system (Figure 9).

Conditional on the occurrence of the human error of type (Oj, Figure 8), the probability that the error gets through the QA / QC system can be developed as follows. The probability of detection is P[D] and the probability of correction is P[C]. The compliments of these probabilities (not detected and not corrected) will be indicated as $P[\bar{D}] = 1 - P[D]$, and $P[\bar{C}] = 1 - P[C]$.

The undetected and uncorrected error event (Uej) associated with the human error event (Oj) is

$$Ue = \cup \ (Oj \cap \bar{D}j \cap \bar{C}j) \qquad (j = 1 \text{ to } 8) \qquad (17)$$

The probability of the undetected and corrected error of type j event is

$$P[Ue] = \sum P[Oj \mid \bar{D}j \cap \bar{C}j]\ P[\bar{D}j \mid \bar{C}j]\ P[\bar{C}j] \qquad (j = 1 \text{ to } 8) \qquad (18)$$

where $A \cap B$ indicates the intersection of events A and B.

Assuming independent events, the probability of the undetected and corrected error of type j event is

$$P[Uej] = P[Oj]\ \{P[Dj]\ P[\bar{C}] + P[\bar{D}]\} =$$

$$= 1 - P[D]\ P[C] \qquad (19)$$

The probability of error detection and the probability of error correction obviously play important roles in reducing the likelihood of human errors compromising the system quality. Note that in the developments that preceded the introduction of QA / QC considerations, if P[Oj] were replaced with P[Uej], the effects of QA / QC could be introduced into any of the parts of the system.

The probability of detection will be a function of the effectiveness and intensity of the QA / QC directed at this function. Similarly with regard to the probability of acceptable or adequate correction. In both cases, an expenditure of resources is required to achieve the desired objectives. Some limited studies have been conducted to determine the factors that influence P[D] in design (Melchers, 1987a; 1987b; Stewart, 1990).

The problem is to determine where QA / QC efforts should be directed, how they should be directed, and how intensely they should be developed. Given limited resources to develop quality in a marine structure, this is probably the single best reason for quantitative analyses of marine structure systems: to help identify the most effective ways to implement QA / QC efforts throughout the life-cycle of a marine structure.

QA / QC IN DESIGN

This section will outline two QA / QC strategies in design of marine structures. The first strategy addresses the design team and the conduct of its work. The second strategy addresses the design guidelines and software used to perform this work.

Strategy #1 - Design Team

The first line of defense is associated with prevention and minimization of errors made and not corrected by the individuals that perform the design analyses and conduct the design processes. The quality of the structural design is a direct function of the quality of the design team that performs the design. Table 1 summarizes the key factors that need to be addressed to develop a high reliability structure design team . Many of these factors relate directly to the qualities that define "High Reliability Organizations" (Roberts, Bea, 1995).

TABLE 1 - KEY FACTORS IN DEVELOPMENT OF A HIGH RELIABILITY STRUCTURE DESIGN TEAM

Communications	Procedures
Personnel selection	Organization
Training	Leadership
Planning	Monitoring
Preparations	Information seeking
Quality resources	Controlling
Appropriate operation strategies	Information evaluation
Quality incentives & rewards	Distributed decision making
	Discipline & integrity

Past problems associated with design of marine structures (Bea, 1994; Bea et al., 1994) indicates that effective communications, personnel selection, training, provision adequate resources to achieve the desired quality, and provision of quality incentives and rewards are essential elements that determine the frequency and intensity of human factor related problems in structure design.

Communications has been identified as a major human factors problem in many other individual and team situations. The way in which information is presented, information distortion (biasing), and the formatting of the information can have dramatic affects on the effectiveness of the communications within the design team.

Training of design personnel must also match the job to be done. To enhance the performance of a specific task, the more correct repetition that occurs, then the lower the likelihood of error. To enhance problem solving, experience in a variety of tasks is needed. Design personnel need to be trained to perform a wide variety of types of tasks so that they eventually become able to perform a structure design from start to finish. It is this ability to integrate across the design phases that helps eliminate weak-link chain type design processes.

Training of design personnel to understand the effects of biases and heuristics on their decisions is important. Decision makers involved in the design of complex structural systems need to be taught about confirmation bias; the tendency to seek new information that supports one's currently held belief and to ignore or minimize the importance of information that may support an alternative belief. Rigidities in perceptions, ignoring potentially critical flaws in complex situations, rejection of information, and minimizing the potentials for errors or flaws result from confirmation bias.

In design, adequate QC (detection, correction) can play a vital role in assuring the desired quality is achieved in a marine structure. Independent, third-party verification, if properly qualified, directed, and motivated, can be extremely valuable in disclosing embedded errors committed during the design process. Valuable guidelines have been developed by Knoll (1986) and Melchers (1987) for checking structural design work.

In many problems involving insufficient quality in marine structures, embedded errors have been centered in fundamental assumptions regarding the design conditions and constraints and in the determination of loadings. In some cases, these embedded errors have been institutionalized in the form of design codes, guidelines, and specifications (Bea, 1994). It takes an experienced outside viewpoint to detect and then urge the correction of such embedded errors. The design organization must be such that identification of potential major problems is encouraged; the incentives and rewards for such detection need to be provided (Table 1).

It is important to understand that adequate correction does not always follow detection of an important or significant error in design of a structure. Again, QA / QC processes need to adequately provide for correction after detection. Potential significant problems that can degrade the quality of a structure need to be recognized at the outset of the design process and measures provided to solve these problems if they occur.

Strategy #2 - Design Procedures & Software

There are three approaches that should be considered in addressing QA / QC in design procedures:

1) QA / QC the design procedures, processes, and software to help assure technical correctness, accuracy, and completeness, and eliminate unnecessary complexity,

poor organization, and ineffective documentation in the guidelines. (fault avoidance).

2) Integrate QA / QC requirements directly into the design procedures and processes (fault detection, correction).

3) Introduce measures into the design procedures and processes that will minimize the effects of HOF on the quality of the structure (fault tolerance).

Current experience indicates that if not properly developed and documented, a design guideline can enhance the likelihood of significant errors being made by even experienced structural designers. These errors can lead to important compromises in the intended quality of the structure. The errors arise primarily because of the dramatically increased complexity of the design guideline, its similarly increased "opaqueness" (frequently caused by associated computer software), and the lack of sufficient training.

The more difficult a task is made, then the more likely that there will be errors. Those charged with development of structure design guidelines should be sensitized to these factors. Design guidelines should be developed that will minimize the difficulty of the tasks to be performed and thereby enhance the likelihood of high quality design results.

The design procedure quality attributes of intuitive, first principles, and empirical verifications are extremely important. Intuitive verifications are derived from the designer "feel" based on good and bad experience. This feel is responsible for a majority of quality problems that are detected and corrected (design "near misses").

First principles verification is needed so that complexity is not allowed to over-shadow realism. This means first that design engineers need to be well trained in these first principles, and second, that the design process must encourage their use in verifying the results from the analyses.

Experience has indicated that results from simplified methods that employ first principles can play an important role in identifying problems in results from complex methods (Bea, Mortazavi, 1995; Bea, Loch, Young, 1995). Often, there is little "respect" given to such methods by engineers and researchers alike. They feel that complex methods are more elegant and give more realistic results. Sophistication in analyses does not assure either reliability or realism in results. There is an important need to further develop simplified design methods that can be used to help verify results from complex analyses.

Empirical or experimental verification is needed because of the inherent inadequacies and limitations of most engineering analytical procedures when applied to design of structures. This is particularly true when it comes to loading analyses, but it also applies to most structure analyses. The question is the extent of experimental verification that is required. This becomes a problem in trading-off the costs involved in providing the verification versus the costs involved when insufficient quality is obtained due to the lack of the verification (Wenk, 1986).

It is rare to find explicit structure design guidelines that explicitly address the need for obtaining human error tolerance in the life-cycle of any type of structure (Bea, 1991). Some have begun to appear (e.g. Das, Garside, 1991), but more work is needed to develop such guidelines. This is one of the most important areas for marine structures research.

Structure robustness can be achieved with a combination of redundancy, ductility, and excess capacity in the structure system. Robustness implies much more than redundancy (degree of indeterminacy) (Das, Garside, 1991). Fail-safe design is one aspect of this approach (Bea, 1992).

Robustness needs to be placed in those areas of the structure that have high probabilities of damage or defects and high consequences associated with such damage or defects. Such an approach has been used recently in design of several major offshore platforms (Bea, 1991). The approach had major effects on the configuration of the structures.

CONCLUSIONS

A classification system has been developed to characterize how compromises in quality of marine structures can be developed by individuals, organizations, equipment, procedures, and environments. A quantitative probability based formulation has been developed to analyze the reliability characteristics of the structure throughout its life-cycle. QA / QC alternatives have been discussed that can be considered to improve the quality of marine structures. The influences of QA / QC have been integrated into the probability based formulation.

A companion paper [Bea, 1995] discusses use of qualitative and quantitative based methods in evaluating the quality of marine structures. Application of these methods to the design of critical structural details for fatigue durability is illustrated.

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